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14. ABSTRACT
The purpose of this project proposal was to acquire several key equipment items, which were critical to establish the proposed Center for Hybrid Communications & Networks related to both classical and quantum channels. The requested items were: (1) four PLUTO-TELCO Phase Only Spatial Light Modulators (SLMs), (2) Tektronix digital real-time oscilloscope, and (3) three single-photon detectors (system model: COUNT-Q - single photon counting modules, 950 nm to 1600 nm).

15. SUBJECT TERMS
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a. REPORT	b. ABSTRACT	c. THIS PAGE			Ivan Djordjevic
UU	UU	UU	UU		19b. TELEPHONE NUMBER 520-626-5119

Report Title

Final Report: Center for Hybrid Communications and Networks

ABSTRACT

The purpose of this project proposal was to acquire several key equipment items, which were critical to establish the proposed Center for Hybrid Communications & Networks related to both classical and quantum channels. The requested items were: (1) four PLUTO-TELCO Phase Only Spatial Light Modulators (SLMs), (2) Tektronix digital real-time oscilloscope, and (3) three single-photon detectors (system model: COUNT-Q - single photon counting modules, 950 nm to 1600 nm).

The proposed equipment augment ongoing research activities at the University of Arizona in the areas of intelligent optical aggregation networks, high-rate QKD for marine environment, cognitive hybrid optical-wireless networking (CHOWN), and free-space optical communications.

The acquired equipment has enabled us to study the feasibility of future hybrid communication networks and beyond, the OAM-based QKD, as well as to initiate establishment a Center for Hybrid Communications & Networks. We believe that successful experimental demonstrations of our current CHOWN research will be of higher relevance to ongoing DOD efforts to ensure that defense networks sustain high data rates under diverse weather and interference scenarios. On the other hand, our research in high rate multidimensional QKD in a desert environment will enable the increase of data rates for several orders in magnitude.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 1.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Thanks to DURIP 2015 support, we were able to build three experimental setups:
1) Indoor free-space optical (FSO) experimental setup to study OAM-based FSO communication over strong atmospheric turbulence channels;
2) Transmission loop experimental setup to study coded modulation and turbo equalization for metro and long-haul networks,
3) Experimental setup for multidimensional QKD studies.
Additionally, we are able to build the FSO transceiver, which will be used in planned outdoor FSO experimental setup.

Technology Transfer

DURIP 2015 PROJECT REPORT

TABLE OF CONTENTS

1. INTRODUCTION

The purpose of this project proposal was to acquire several key equipment items, which were critical to establish the proposed **Center for Hybrid Communications & Networks related to both classical and quantum channels**. The requested items were: (1) four PLUTO-TELCO Phase Only Spatial Light Modulators (SLMs), (2) Tektronix digital real-time oscilloscope, and (3) three single-photon detectors (system model: COUNT-Q - single photon counting modules, 950 nm to 1600 nm).

The proposed equipment augment ongoing research activities at the University of Arizona in the areas of intelligent optical aggregation networks, **high-rate QKD for marine environment**, cognitive hybrid optical-wireless networking (CHOWN), and free-space optical communications. Some of these activities have currently supported by grants from the ONR and the National Science Foundation (NSF) ERC CIAN. The first project is related to the increase in the information bandwidth and improvement of energy efficiency, represented key problems relevant in both aggregation and data center networks. Additionally, the dynamic bandwidth allocation and distribution is also relevant. The purpose of this project to address all these issues in a simultaneous manner. The project goals can be summarized as follows: (i) maximize spectral efficiency and optimize energy efficiency; (ii) enable adaptive allocation of error correction strength for IANs and data centers; (iii) implement adaptive coding module for agile coherent transceivers; (iv) employ adaptive multidimensional coded modulation and multiplexing with frequency, time, space, and polarization basis functions.

The second project represents a collaborative effort between the University of Illinois, Duke University, University of Arizona (co-investigators: I. B. Djordjevic and M. Neifeld) and Boston University. In this project we have proposed a comprehensive, basic science investigation of *agile* QKD strategies that can automatically adjust for optimal performance in the highly variable environment encountered over the sea deck and can operate at secure rates exceeding 100 Mb/s. We pursue two complementary approaches, undertaking fundamental studies of QKD systems that use (hyper-) entangled photon pairs or weak coherent states (WCS) as the quantum resources.

The third activity, related to classical FSO communications and hybrid FSO-RF, was supported in part by NSF and AFOSR through STTR program, and currently supported by Dr. Djordjevic's discretionary account. CHOWN is motivated by the need to maintain high-throughput communications at all times, under diverse weather/interference conditions. In particular, future military networks are being designed to support a wide range of services, carrying a large amount of multimedia traffic over different network types at very high speeds. The performance of these networks can be greatly impacted by various link impairments, related to environmental factors (e.g., weather conditions) as well as adversarial effects (e.g., jamming). HOWN offers a paradigm for operating different transmission technologies in a complimentary manner. The focus of our HOWN research is on hybrid FSO/RF communications, although other hybrid forms of communications can benefit from the outcomes of this effort. FSO has many attractive features, including: (i) very high directivity of the optical beam, which provides high power efficiency and spatial isolation from other potential interferers (a property not inherent in typical broadcast-based wireless communications), (ii) FSO transmissions are unlicensed, and (iii) FSO's large fractional bandwidth permits multi-Gb/s rate transmission using moderate transmission powers. Because of its flexibility, FSO transmissions can be deployed at various locations in the network (e.g., core, edge, access, etc.) [1], [2], and can be used over inter-satellite links, satellite-to-ground, satellite-to-ship, etc. Yet, despite these advantages, large-scale deployment of FSO systems has so far been hampered by reliability and availability issues, related to atmospheric turbulence in clear weather and low visibility in foggy conditions. In contrast, RF signals are not impacted by these problems, but are affected by other issues, particularly rain and snow. This suggests that the two channels (FSO and RF) can be jointly operated in an almost complementary fashion, depending on the prevailing weather conditions. We refer to such a joint operation as "hybrid FSO/RF link." The FSO subsystem will use OAM modulation, while RF subsystem conventional QAM.

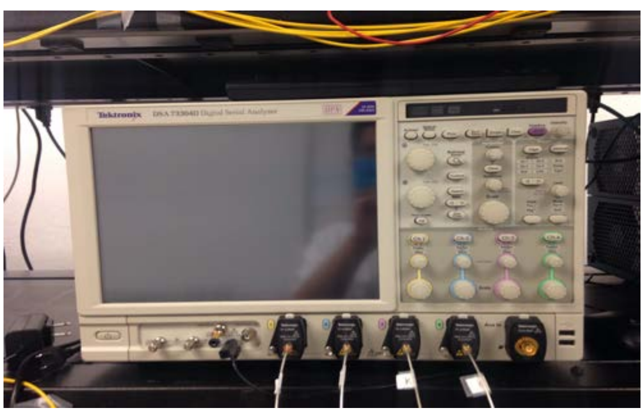
Regarding our **research in high-rate multidimensional QKD**, we study the fundamental and practical problems related to generation, entanglement, propagation and detection of photons in **quantum free-space optical transmission in a desert environment**, as well as advanced QKD solutions that can increase the information rate per photon in challenging atmospheric conditions, while improving security with respect to both individual and coherent attacks.

The acquired equipment has enabled us to study the feasibility of future hybrid communication networks and beyond, the OAM-based QKD, as well as to initiate establishment a **Center for Hybrid Communications & Networks**. We believe that successful experimental demonstrations of our current CHOWN research will be of higher relevance to ongoing DOD efforts to ensure that defense networks sustain high data rates under diverse weather and interference scenarios. On the other hand, our research in high rate multidimensional QKD in a desert environment will enable the increase of data rates for several orders in magnitude.

The rest of the report is organized as follows. In Section 2, we describe the research instrumentation acquired by this grant. In Section 3, we describe the impact of acquired equipment. In Section 4, we describe the relevance of purchased equipment to active DoD grants. Section 5 is devoted to the expense report. Finally, in Section 6, some relevant research activities benefiting from acquired equipment are described. In Appendix, University of Arizona Final Property Report is provided.

2. DESCRIPTION OF THE ACQUIRED RESEARCH INSTRUMENTATION

To validate our **research agenda on hybrid FSO/RF communications**, several proof-of concept-experiments have been performed using the acquired equipment. Initially, these experiments have been conducted using indoor benchtop optical equipment, whereby propagation conditions can be carefully controlled. Later on, we plan to deploy a multi-channel hybrid FSO/RF system for outdoor communication. This system will comprise a multi-channel transmit/receive station, located in the ECE building, and a set of retro-reflectors located elsewhere on campus.



(a)

(b)

Fig. 1 (a) Tektronix DPO72304DX 23 GHz Digital Phosphor Oscilloscope purchased by this grant. (c) Tektronix arbitrary waveform generator also acquired by this grant.

Thanks to this grant, we were able to acquire a Tektronix digital serial analyzer DSA 73304D of 33 GHz bandwidth and sampling rate 100 GSa/s, shown in Fig. 1(a), as well as a Tektronix two-channels-based arbitrary waveform generator AWG70002A of bandwidth 10 GHz and sampling rate of 25 GS/s, shown in Fig. 1(b), for the price of lower than that of single Tektronix DPO72304DX 23 GHz Digital Oscilloscope from the initial quote. Dr. Djorjevic was able to convince Tektronix manages to provide huge University discounts, after long negotiation process. This real-time digital communication analyzer allow us to observe four channels simultaneously in all available modes. Now we are in position to detect both polarization states simultaneously, which is important for coded modulation and turbot eluviation studies for high-speed fiber-optics communications. Additionally, we are able to generate two OAM channels simultaneously each carrying independent QAM signals, which is of high important for FSO communication studies. With two-channels-based AWG we are able to generate arbitrary two-dimensional signal constellations for study in both FSO and fiber-optics communications.

Further, from DURIP 2015 grant we were able to purchase four PLUTO-TELCO spatial light modulators, as shown in Fig. 2. Two of SLMs are used to generate and detect desired OAM modes, respectively. The other two SLMs are used to build strong atmospheric turbulence emulator for study of FSO communication over strong atmospheric turbulence channels.

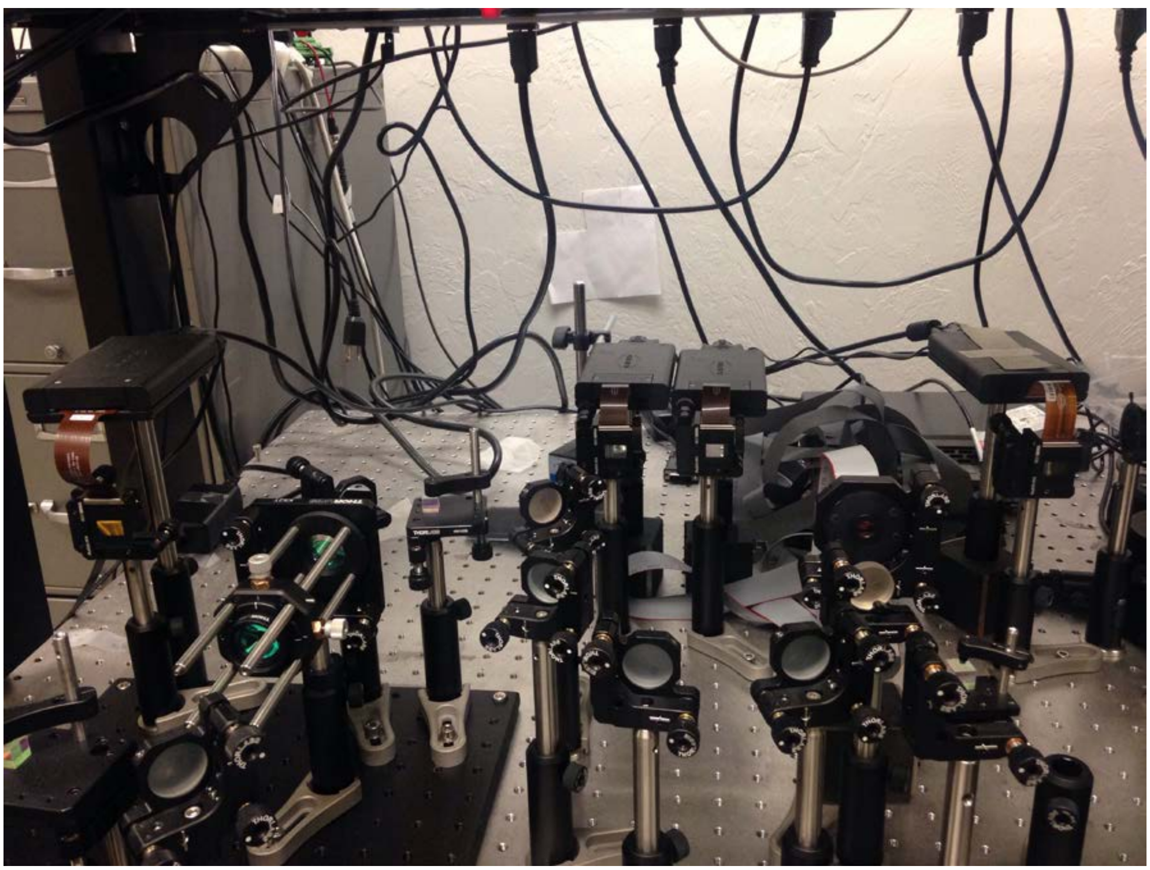
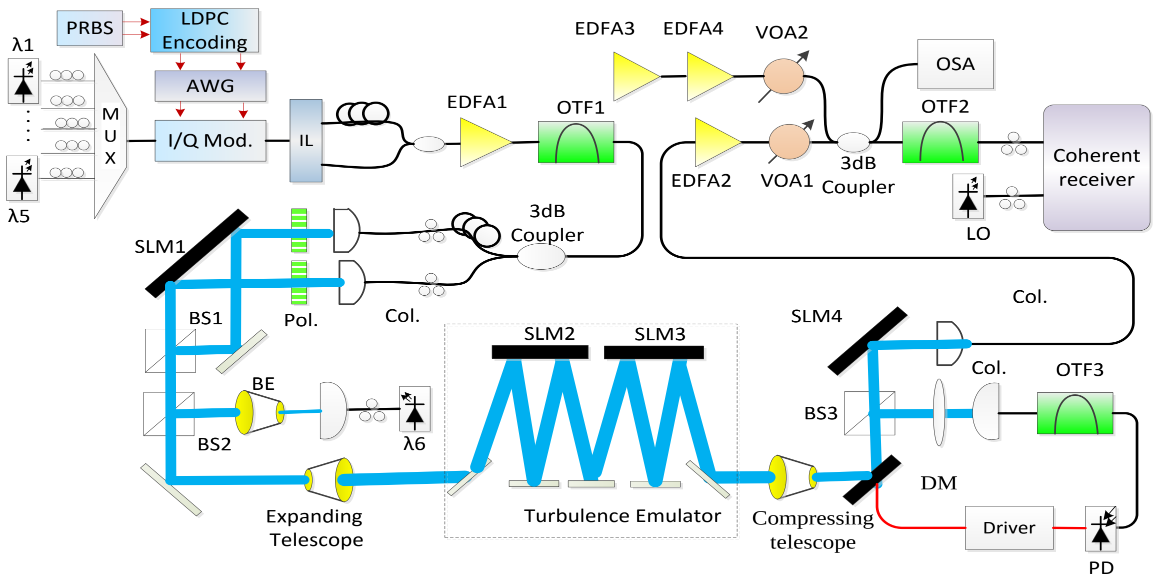
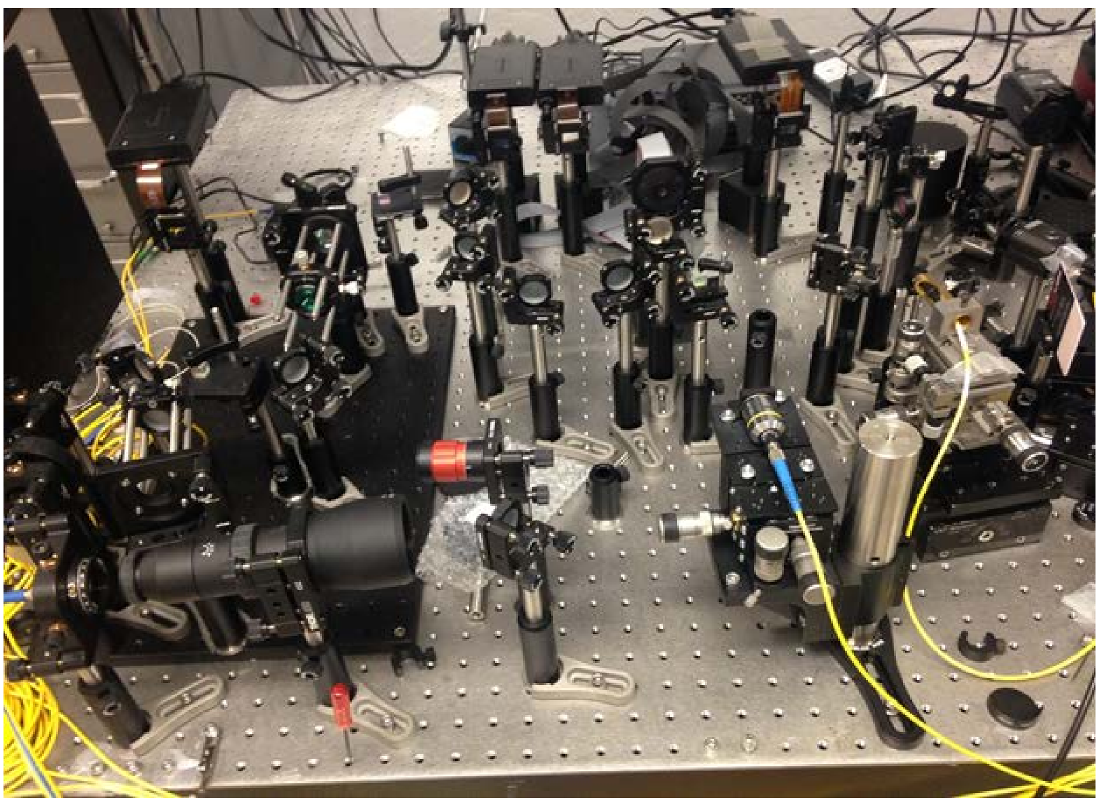


Fig. 2 PLUTO-TELCO spatial light modulators from Holoeye purchased from funds provided by DURIP 2015 grant as a part of OAM-based FSO communication system. Two inner SLMs serve as strong atmospheric turbulence emulator.

The overall FSO indoor experimental setup we were able to build up thanks to the DURIP 2015 award is shown in Fig. 3. Full details of this setup will presented at incoming IEEE ICTON conference, where we have an invited paper [P-1] to present. Additionally, we were able to publish two invited chapters, buy using a simplified experimental setup [P-2],[P-3]. We plan to extend this setup for outdoor FSO experiments as illustrated in Fig. 4. The corresponding transceivers has already been implemented as shown in Fig. 2(b). Namely, this FSO transceiver is implemented on such a way that can be used in both indoor and outdoor FSO experiments. Unfortunately, this outdoor FSO setup can only be used in weak turbulence regime since existing adaptive optics kit, available in the Lab is too slow for outdoor applications. Additional investment will be needed in this area.



(a)



(b)

Fig. 3 (a) Indoor FSO experimental setup for study of OAM-based FSO communication over strong atmospheric turbulence channels. (b) Corresponding phot of the experimental setup.

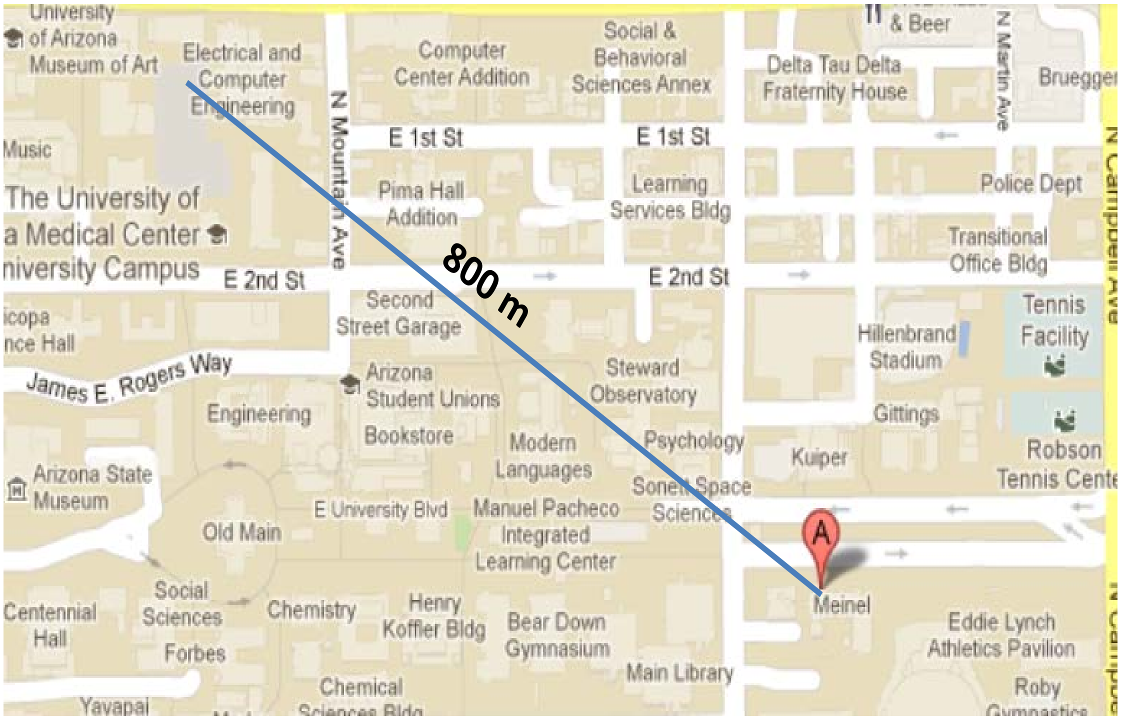


Fig. 4 Map illustrating planned location of the FSO link to be established at the University of Arizona facilities (between ECE Department building and College of Optical Sciences building).

[P-1] Z. Qu, I. B. Djordjevic, "Approaching terabit serial optical transmission over strong atmospheric turbulence channels," in Proc. *IEEE ICTON 2016*, Paper Tu.A2.3, Trento, Italy, July 10-14, 2016. (**Invited Paper**.)

[P-2] I. B. Djordjevic, Z. Qu, "Coded Orbital Angular Momentum Modulation and Multiplexing Enabling Ultra-High-Speed Free-Space Optical Transmission," in *Optical Wireless Communications - An Emerging Technology*, (M. Uysal, C. Capsoni, Z. Ghassemlooy, A. Boucouvalas, E. G. Udvary, Editors), Springer, 2016.

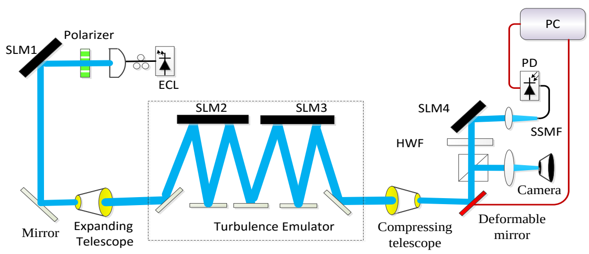
[P-3] I. B. Djordjevic, Z. Qu, "Coded Orbital-Angular-Momentum-Based Free-Space Optical Transmission," in *Wiley Encyclopedia of Electrical and Electronics Engineering*, Feb. 2016. [Available at http://onlinelibrary.wiley.com/doi/10.1002/047134608X.W8291/abstract]

The real-time scope and AWG are also used in fiber-optics transmission loop experiment we build in the Lab to study different coded modulation and turbo equalization schemes suitable for metro and long-haul networks.

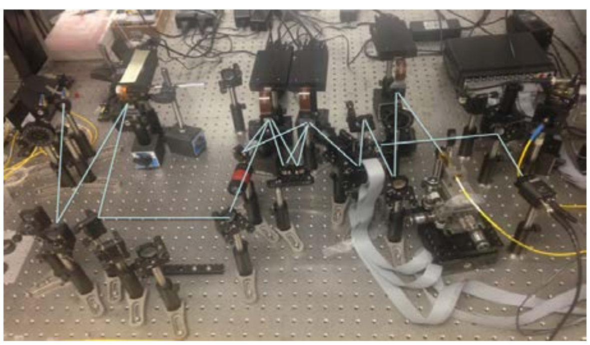
The purchase of single-photo detectors COUNT-Q, shown in Fig. 5, has enabled us to build up the multidimensional QKD experiment, which will be used in ONR MURI project during this summer and in incoming academic year 2016/2017. Dr. Djordjevic was able to convince Laser Components to sell us four single-photon detector modules for the price of three COUNT-Q modules from initial quote.

From the saving we were able to get by long negotiation process with Tektronix thanks to the huge university discount, we were able to save some money which accounts for half the price to purchase the wavefront sensorless adaptive optics kit together with multi-DM MEMS deformable mirror equipment from Boston Micromachines Corporation (BMC) to deal with atmospheric turbulence effects, which is illustrated in Fig. 6. For the other half of expenses, we were using the funds available for equipment in MURI ONR grant.

Fig. 5 COUNT-Q single-photon detectors from Laser Components purchased by this grant used in multidimensional QKD experiments.



(a)



(b)

Fig. 6 Initial experimental setup for correction of azimuthal phase distortions by adaptive optics: (a) experimental setup, (b) photo of actual experiment.

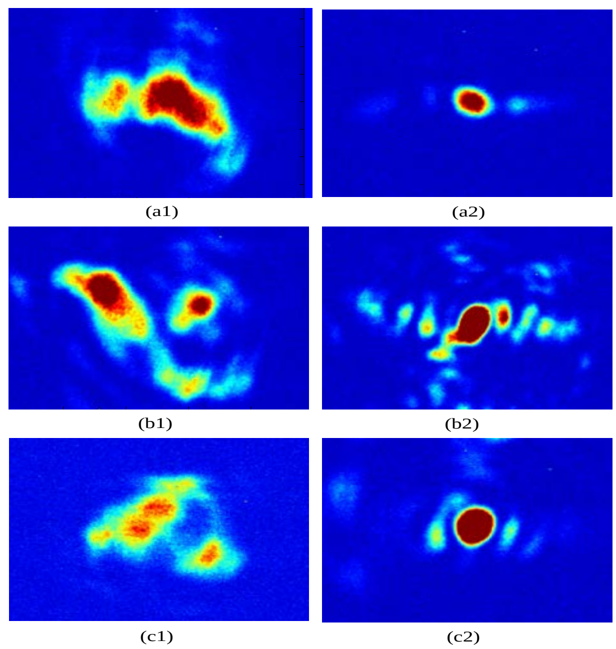


Fig. 7 The effects of adaptive optics (AO) in medium atmospheric turbulence: (a1), (b1), (c1) are the intensity profiles without AO compensation; (a2), (b2), (c2) are the intensity profiles after AO compensation.

The initial results demonstrating effectiveness of adaptive optics in managing atmospheric turbulence effects are shown in Fig. 7.

3. IMPACT OF ACQUIRED EQUIPMENT AND RESEARCH ACTIVITIES

The proposed research activities in CHN will help to solve several important technological challenges: (i) the incompatibility of RF/microwave and optical communication technologies due to the large bandwidth mismatch between RF and optical channels, (ii) integrating the FSO and fiber-optic networks, (iii) integrating wireless (RF) and optical technologies, (iv) developing efficient coded-modulation schemes capable to operate under the strong atmospheric turbulence (present in FSO portion of the hybrid network), multipath wireless fading, and in the presence of intra-channel nonlinearities, PMD and residual chromatic dispersion (present in fiber-optic links). New technological and experimental breakthroughs in the area of hybrid RF-optical networks are of utmost importance. By combining the theoretical expertise in coding, modulation, protocol design, FSO communications, and fiber-optics communications with the numerical modeling expertise and the state-of-the-art experimental infrastructure at the University of Arizona (UA), thanks to DURIP 2015 grant, we are now in a unique position to successfully carry out this multidisciplinary research initiative and to develop the new generation of hybrid communication systems and networks.

Most research efforts today in quantum key distribution (QKD) have focused on two-dimensional QKD, commonly by use of the polarization state of photons. Moreover, the data rates for quantum key exchange are still low, while transmission distance is limited. On the other hand, it is well known that photons can carry both spin angular momentum (SAM) and orbital angular momentum (OAM), associated with polarization and azimuthal phase of the complex electric field, respectively. Accordingly, we can associate a total angular momentum (TAM) to a sum of SAM and OAM of each photon. Since OAM eigenstates are orthogonal, an arbitrary number of bits per single photon can be transmitted. Thanks to single-photo detectors acquired with the help of DURIP 2015 grant, we have been able to start a multidisciplinary research initiative that focuses on the development and understanding of schemes multidimensional QKD (MQKD) over FSO channels, which would directly benefit DoD since it points to solutions for the most secure communications at higher speeds.

4. Relevance to Active DOD Projects

Dr. Djordjevic is a co-investigator on the following active DOD project, which will directly benefit from the proposed research instrumentation:

***Project Title*: Fundamental Research on Wavelength-Agile High-Rate Quantum Key Distribution (QKD) in a Marine Environment**

***Sponsor*: ONR MURI**

***Duration*: July 2013 to June 2018**

***Program Manager*: Dr. Carey Schwartz**

PI: Paul Kwiat, University of Illinois at Urbana-Champaign

Co-Investigators from University of Arizona: Ivan B. Djordjevic and Mark Neifeld

Amount of funds allocated to University of Arizona: $ 1,858,104

***Project Summary*:** This project is a collaborative effort between the University of Illinois, Duke University, University of Arizona (co-investigators: I. B. Djordjevic and M. Neifeld) and Boson University. We proposed a comprehensive, basic science investigation of *agile* QKD strategies that can automatically adjust for optimal performance in the highly variable environment encountered over the sea deck and can operate at secure rates exceeding 100 Mb/s. In this project, we pursue two complementary approaches, undertaking fundamental studies of QKD systems that use (hyper-)entangled photon pairs or weak coherent states (WCS) as the quantum resources. However, the idea of using the orbital angular momentum (OAM) to create multidimensional entanglement for quantum key distribution in free space that has not been studied at all in this research. This research will directly benefit from proposed equipment acquisition grant. The OAM will also be used as additional degree of freedom to improve the aggregate data rate in classical free-space optical links. The requested spatial light modulators and real-time scope will enable to establish the Cognitive OAM-based Free-Space Optical Communication Testbed, in which both classical and quantum OAM-based FSO communication systems will be studied.

5. EXPENSE REPORT

There are several equipment items that we were able to purchase with this grant:

1. Tektronix digital communication analyzer (DSA 73304D) and arbitrary waveform generator (AWG 70002A)
    - Total price: $427,000
    - Various University/Educational/Charitable Discounts: $ - 277,086.25
    - **Net price: $149,913.75**
2. Four HES601-TELCO-013-C Spatial Light Modulators (SLMs):
    - Four SLMs: $ 15,990 × 4=$63,960
    - Discount: $ -13,960
    - Shipping, Insurance and Handling: $360
    - **Net price: $ 50,380**
3. Four COUNT-Q- single photon counting modules, 950 nm to 1600 nm
    - **COUNT-Q modules net price: $ 50,400**
4. Wavefront sensorless adaptive optics kit together with multi-DM MEMS deformable mirror equipment from Boston Micromachines Corporation
    - Total price: $ 26,945
    - MURI ONR portion: $-9370.75
    - **Net price**: **$17,574.25**

Total for All Items: **$ 268,268**

As it can be seen from Table 1 below, all funds received from this DURIP award have been spent.

The corresponding invoices are provided in the rest of this section.

Table 1: University of Arizona's table of expenses

The University of Arizona

Run Date: 4/5/2016

UAccess Analytics - Financials

Page 1 of 1

Income / Expense

Account Number	Consolidation Object Name	Original Budget	Base Budget	Current Budget	Current Month Actuals	Fiscal Year Actuals	Inception to Date	Open Encumbrances	Pre-Encumbrance	Balance Available
3015210	CAPITAL	0.00	0.00	268,268.00	(45.02)	268,268.00	268,268.00	0.00	0.00	0.00
	EXPENSES Total	**0.00**	**0.00**	**268,268.00**	**(45.02)**	**268,268.00**	**268,268.00**	**0.00**	**0.00**	**0.00**
3015210 Total		**0.00**	**0.00**	**268,268.00**	**(45.02)**	**268,268.00**	**268,268.00**	**0.00**	**0.00**	**0.00**
Grand Total		**0.00**	**0.00**	**268,268.00**	**(45.02)**	**268,268.00**	**268,268.00**	**0.00**	**0.00**	**0.00**

Fiscal Year is equal to **2016**
and Basic Accounting Category Code is equal to **IN , EX**
and Basic Accounting Category Code is equal to **EX**
and Period Number is equal to **09**
and Organization-Code is equal to **2303**
and Sub Account Type Code is equal to - , **EX**
and Chart Code is equal to / is in **UA**
and Account Number is equal to **3015210**

lowem
9/9/2015, 11:07 AM
EMAIL

Tektronix

Tektronix Inc
MS 60-295 Sales Support West
PO Box 500
Beaverton, OR 97077
United States
TEL: 800-833-9200
FAX: 503-627-3247

Invoice No:	**US493752**
Invoice Date:	28-Aug-15
Account-No:	1129
Page:	1 of 2

Customer Contact:	Lila Sorensen
Purchase Order:	276811
Shipping Terms:	FCA TEKTRONIX SHIPPING POINT
Carrier:	
Order No:	MP-2742204
Ship Date:	28-Aug-15

SHIP TO:
University of Arizona
John Long
Elec and Comp Engineering
1230 East Speedway Blvd
Tucson, AZ 85721

BILL TO:
University of Arizona
PO Box 5, Accounts Payable
1303 E University Blvd
Tucson, AZ 85719

PRODUCT	DESCRIPTION	QTY	UNIT PRICE	EXTENDED PRICE	TAX
	Reconditioned product				
	TekSelect products are reconditioned to factory specifications and may show signs of prior use.				
	Sorensen, Lila R - (lilas) <lilas@email.arizona.edu> Djordjevic, Ivan B - (ivan) <ivan@email.arizona.edu> Long, John D - (longj) <longj@email.arizona.edu>				
AWG70002A	Arbitrary Waveform Generator: 2-channel, 2G samples record length, 10 bit Serial No: B010835	1	0.00	0.00	A
AWG70002A 225	25 Gsamples per second	1	123,000.00	123,000.00	A
	25.00% TekSelect Refurbished Discount		-30,750.00	-30,750.00	
	*** **Subtotal**		**92,250.00**	**92,250.00**	
	15.00% Education Discount		-13,837.50	-13,837.50	
	*** **Subtotal**		**78,412.50**	**78,412.50**	
	Fixed Amount Charitable Donation		-18,768.75	-18,768.75	
	** **Subline Total**		**59,643.75**	**59,643.75**	
AWG70002A 01	Add waveform memory expansion (128 Mpoint to 8 Gpoint)	1	10,000.00	10,000.00	A
	25.00% TekSelect Refurbished Discount		-2,500.00	-2,500.00	
	*** **Subtotal**		**7,500.00**	**7,500.00**	
	15.00% Education Discount		-1,125.00	-1,125.00	
	** **Subline Total**		**6,375.00**	**6,375.00**	
AWG70002A 03	Add sequencing	1	10,000.00	10,000.00	A
	25.00% TekSelect Refurbished Discount		-2,500.00	-2,500.00	
	*** **Subtotal**		**7,500.00**	**7,500.00**	
	15.00% Education Discount		-1,125.00	-1,125.00	
	** **Subline Total**		**6,375.00**	**6,375.00**	
	* **Line Total**		**72,393.75**	**72,393.75**	A
DSA73304D	33 GHz Digital Serial Analyzer; 4 analog channels Serial No: B241033	1	304,000.00	304,000.00	A
	70.00% TekSelect Refurbished Discount		-212,800.00	-212,800.00	
	*** **Subtotal**		**91,200.00**	**91,200.00**	
	15.00% Education Discount		-13,680.00	-13,680.00	
	** **Subline Total**		**77,520.00**	**77,520.00**	
	* **Line Total**		**77,520.00**	**77,520.00**	A

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Continued
Original Invoice MP-291

Tektronix
Tektronix Inc
MS 60-295 Sales Support West
PO Box 500
Beaverton, OR 97077
United States
TEL: 800-833-9200
FAX: 503-627-3247

Invoice No:	**US493752**
Invoice Date:	28-Aug-15
Account-No:	1129
Page:	2 of 2

PRODUCT	DESCRIPTION	QTY	UNIT PRICE	EXTENDED PRICE	TAX
	Tektronix now offers order status online at www.tektronix.com (click on order status). Your customer account number is located on this document.				
	EDUCATIONAL DISCOUNT AND/OR CHARITABLE CONTRIBUTION IS CONDITIONAL UPON TITLE REMAINING WITH THE INSTITUTION. NOT VALID IF PRODUCT IS RESOLD.				

SHIP/HNDL	ITEM TOTAL	TAX		INVOICE AMOUNT
	US$ 149,913.75	A- 0.00% Arizona Tax Exempt - 2742204	US$ 0.00	**US$ 149,913.75**

PAYMENT TERMS: Net 30 Due Date: 27-Sep-15
Remit to: **ACH Routing #121000358 (CTX Preferred) Acct# 12331-19002**
Check Payments: Tektronix Inc, P.O. Box 742644
Los Angeles, CA 90074-2644

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EQUAL OPPORTUNITY EMPLOYER
Tektronix Tax US 93-0343990

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Original Invoice MP-201

sjvn
9/28/2015, 9:01 AM
EMAIL

HOLOEYE Corporation
1620 Fifth Avenue,
Suite 550
San Diego, CA 92101
USA
Phone: (888) 446-5639, ext. 110
Fax: (888) 446-5539
contact@holoeyecorp.com
www.holoeyecorp.com

President/CEO: Marcel Rogalla

HOLOEYE Corporation, 1620 Fifth Avenue, Suite 550, San Diego, CA 92101, USA

University of Arizona
Accounts Payable
1303 E. University Blövd. PO Box 5.
TUCSON, AZ 85719-0521

USA

09/28/2015

Invoice No. 91-15-C-17614

[PO Number: 276634; Date 09/04/2015; Buyer: Celeste D. Kanzig]

POS	Item	Description	Qty.	Unit-Price	Total Amount
1	HES 6010-TELCO-013-C	PLUTO-TELCO-013-C Phase Only Spatial Light Modulator (1400- 1700 nm, 93% Fill Factor): - Phase only panel incl. flex - Driver unit - Device mount - Display mount - Power supply - DVI-cable - HDMI/DVI cable - RS232 cable & USB to serial adapter - Users manual - USB Flash Drive with driver and application software S/N 6010 1078 S/N 6010 1079 S/N 6010 1080 S/N 6010 1081 Warranty: 12 Months	4	$ 15,990.00	$63,960.00
2	Discount	Price reduction	1	- $ 13,960.00	- $ 13,960.00
				Shipping, Insurance & Handling:	$ 380.00
				Total Amount:	**$ 50,380.00**

The property in the Goods shall not pass to the buyer until HOLOEYE has received payment in full of the price agreed.

Payment by credit transfer to bank-account:

Details of Payment:	**Name:**	**HOLOEYE Corporation**
	A/C-No:	**526 353 987**
	Routing-No.	**322 271 627**
	Bank:	**JP Morgan Chase bank, San Diego, CA 92107** **1881 Sunset Cliffs Blvd.**

Terms of payment: **15 days net – free of bank charges for us**

Please accept our best thanks for your order.

HOLOEYE **Pioneers in Photonic Technology**

Laser Components USA, Inc.
116 South River Road
Building C
Bedford, NH 03110
USA

Voice: 603-821-7040
Fax: 603-821-7041

sjvn
11/19/2015, 8:41 AM
EMAIL

INVOICE

Invoice Number: 66920
Invoice Date: Nov 19, 2015
Page: 1

Duplicate

Bill To:	Ship to:
University of Arizona Accounts Payable, PO Box 5 1303 E University Blvd. Tucson, AZ 85719-0521 USA	See notes. .

Customer ID	Customer PO	Payment Terms	
Univ AZ CK	276632	Net 30 Days	
Sales Rep ID	**Shipping Method**	**Ship Date**	**Due Date**
Paul Buettner	UPS GR PP/ADD	11/19/15	12/19/15

Quantity	Item	Description	Unit Price	Amount
4.00	3008155	COUNT-Q, Photon Counting Module, InGaAs. -----DELAY REQ: ASAP SHIP BY: 11/19/15 ----- SHIPPING ADDRESS: University of Arizona ATTN: John D Long Electrical & Computer Engineering Route Code: TB, Room #268 1230 E Speedway Blvd. Tucson, AZ 85719 ----- Order will ship 11/19/15 via UPS Ground prepaid and added to the invoice; FOB: Bedford, NH. Email confirmation to: cdkanzig@email.arizona.edu & ivan@email.arizona.edu	12,500.00	50,000.00

Subtotal	Continued
Sales Tax	Continued
Freight	Continued
Total Invoice Amount	Continued
Payment/Credit Applied	
TOTAL	**Continued**

Check/Credit Memo No:

Laser Components USA, Inc.
116 South River Road
Building C
Bedford, NH 03110
USA

Voice: 603-821-7040
Fax: 603-821-7041

INVOICE

Invoice Number: 66920
Invoice Date: Nov 19, 2015
Page: 2
Duplicate

Bill To:	Ship to:
University of Arizona Accounts Payable, PO Box 5 1303 E University Blvd. Tucson, AZ 85719-0521 USA	See notes. .

Customer ID	Customer PO	Payment Terms	
Univ AZ CK	276632	Net 30 Days	
Sales Rep ID	**Shipping Method**	**Ship Date**	**Due Date**
Paul Buettner	UPS GR PP/ADD	11/19/15	12/19/15

Quantity	Item	Description	Unit Price	Amount
		Email invoice to: invoices@fso.arizona.edu		
		In reference to Quotation No. PB080715UA		
		Order is subject to LCUSA standard terms and conditions provided upon request.		

Subtotal	50,000.00
Sales Tax	
Freight	46.07
Total Invoice Amount	50,046.07
Payment/Credit Applied	
TOTAL	**50,046.07**

Check/Credit Memo No:

BOSTON MICROMACHINES CORPORATION
30 Spinelli Place | Cambridge, MA 02138
T: 617 868 4178 | F: 617 868 7996

sjvn
12/22/2015, 11:39 AM
EMAIL

Invoice

Date	Invoice #
12/22/2015	I-15154

Bill To
The University of Arizona Accounts Payable 1303 E. University Blvd., PO Box 5 Tucson AZ 85719-0521 invoices@fso.arizona.edu

Please Remit To
Boston Micromachines Corp. 30 Spinelli Place Cambridge, MA 02138

PO/Contract No.	BMC No.	Terms
294825	SO-15163	Net 30

Qty	Description	Rate	Amount
1	Multi-DM MEMS Deformable Mirror - Continuous Surface - 140 Actuators - 12 Actuators across square active aperture - 3.5 um Max Stroke - 4.4 mm aperture - 400 um pitch - Gold Coating - Protective Window on 6° Wedge w/ AR Coating: 1050-1620 nm	17,500.00	17,500.00
1	Multi-Driver - 140 Channels - 8 kHz / 30 kHz Frame Rate (Stream) - 14 bit Resolution - USB 2.0 Control - Interface Cabling - Demo Software Included	0.00	0.00
1	Multi interface	0.00	0.00
1	Accessories	0.00	0.00
1	Wavefront Sensorless Adaptive Optics Fundamentals Kit for Laser Applications	7,500.00	7,500.00
1	Shipping & handling	195.00	195.00
1	Additional 1 year warranty	1,750.00	1,750.00
		Total	$26,945.00

6. DESCRIPTION OF RESEARCH ACTIVITIES BENEFITING FROM THE ACQUIRED EQUIPMENT

6. 1 Coded Hybrid Orthogonal Frequency Division Multiplexing

The coded-modulation scheme, proposed in this section, is based on coded-OFDM with coherent detection. Notice that coded-OFDM scheme with direct detection has already been proposed by authors in [9], as a scheme that in combination with interleaving is able to operate under the strong atmospheric turbulence. The use of coherent detection offers the potential of even 24 dB improvement over uncoded direct detection counterpart. One portion of improvement (10-13 dB) is coming from the fact that coherent detection can approach quantum-detection limit easier than direct detection. The second portion (about 11 dB) is coming from the use of large-girth LDPC codes [1], [6], [10]. For simplicity, we observe the concatenated hybrid links in this section, while the parallel hybrid links are discussed in Section 6.3. Let us now describe the operation principle of coded-OFDM scheme with coherent detection employing both polarizations. Due to the fact the signal for hybrid FSO-RF communication link is going to be transmitted over the FSO, RF and fiber-optic links, we use a particular polarization-multiplexing capable of eliminating the influence of PMD. By using the retro-reflectors the FSO systems can be applied even when there is no line of sight between transmitter and receiver. Another possibility to extend the transmission distance of FSO systems is to use the amplify-and-forward scenario, as indicated above. The bit streams originating from m different information sources are encoded using different (n,k_i) LDPC codes of code rate $r_i=k_i/n$. k_i denotes the number of information bits of ith (i=1,2,…,m) component LDPC code, and n denotes the codeword length, which is the same for all LDPC codes. The use of different LDPC codes allows us to optimally allocate the code rates. If all component LDPC codes are identical, the corresponding scheme is commonly referred to as BICM. The outputs of m LDPC encoders are written row-wise into a block-interleaver block. The mapper accepts m bits at time instance i from the (mxn) interleaver column-wise and determines the corresponding M-ary ($M=2^m$) signal constellation point $(\phi_{I,i},\phi_{Q,i})$ in two-dimensional constellation diagram such as M-ary phase-shift keying (PSK) or M-ary QAM. The OFDM symbol is generated as described below. N_{QAM} input QAM symbols are zero-padded to obtain N_{FFT} input samples for inverse fast Fourier transform (IFFT) (the zeros are inserted in the middle rather than at the edges), and N_G non-zero samples are inserted to create the guard interval. After D/A conversion, the OFDM signal is converted into the optical domain using the dual-drive Mach-Zehnder modulators (MZMs). Two dual-drive MZMs are needed, one for each polarization, and both of them are available in Lab. The outputs of MZMs are combined using the polarization beam combiner (PBC). The same distributed feedback (DFB) laser is used as CW source, with x- and y-polarizations being separated by a polarization beam splitter (PBS). The operations of all other blocks in transmitter are similar to those we reported in [7],[9].

The main idea of or proposal is to use the OFDM with a large number of subcarriers and in combination with interleavers to overcome atmospheric turbulence and wireless multipath fading. For the OFDM scheme applied in a hybrid environment with a connection to optical fiber links (see Fig 8c) to be capable of simultaneously compensating for chromatic dispersion and PMD; in addition to the atmospheric turbulence, the cyclic extension guard interval should be longer than total delay spread due to chromatic dispersion, DGD and rms multipath delay spread (in wireless subsystem). Because for high-speed signals a longer sequence of bits is affected by the deep fade in the ms range due to atmospheric turbulence, we propose to employ the polarization-multiplexing and large QAM constellations in order to achieve the aggregate data rate of even R_D=100 Gb/s, while keeping the OFDM signal bandwidth in the order of 10 GHz. For example, by using the polarization-multiplexing and 16-QAM we can achieve R_D=100 Gb/s for OFDM signal bandwidth of 12.5 GHz, resulting in bandwidth efficiency of 8 bits/s/Hz. Similarly, by using the polarization-multiplexing and 32-QAM we can achieve the same data rate (R_D=100 Gb/s) for OFDM signal bandwidth of 10 GHz, with bandwidth efficiency of 10 bits/s/Hz.

Initial results. In Fig. 9, we show the initial BER performance of the proposed scheme for both uncoded case (Fig. 9(a)) and LDPC-coded case (Fig. 9(b)). The OFDM system parameters were chosen as follows: the number of QAM symbols N_{QAM}=4096, the oversampling is two times, OFDM signal bandwidth is set to either 10 GHz (M=32) or 12.5 GHz (M=16), and the number of samples used in cyclic extension N_G=64. From Fig. 9 it can be concluded that PMD can be successfully compensated for even in the presence of atmospheric turbulence. The 32-QAM case with aggregate data rate R_D=100 Gb/s performs 1.9 dB (at BER=10^{-6}) worse than 16-QAM (with the same aggregate rate) although the occupied bandwidth is smaller. The net coded gain improvement (at BER of 10^{-6}) of LDPC-coded OFDM over uncoded-OFDM is between 11.05 dB (M=16, σ_X=0.01, σ_Y=0.01, corresponding to the weak turbulence regime) and 11.19 dB (M=16, σ_X=0.1, σ_Y=0.01, corresponding to the medium turbulence regime). The additional coding gain improvement due to transmission diversity with two lasers is 0.19 dB for 32-QAM based OFDM (σ_X=0.01 and σ_Y=0.1) at BER of 10^{-6}. The improvement due to transmission diversity for uncoded case (at the same BER) is 1.26 dB. Therefore, in the regime of weak atmospheric turbulence, the improvements due to transmission diversity are moderate. On the other hand, in the moderate turbulence regime the use of transmission diversity is unavoidable. Otherwise, the uncoded BER error floor is so high (see σ_X=0.5, σ_Y=0.1 curve in Fig. 9(a)) that even the best LDPC codes are not able to handle, if the complexity is to be kept reasonably low. With transmission diversity, in moderate turbulence regime, we obtain BER performance comparable to the case in the absence of turbulence regime, as shown in Fig. 9. Our initial results indicate that proposed coded-OFDM scheme is an excellent candidate to simultaneously deal with scintillation in FSO links, dispersion effect in fiber-optics links and multipath delay spread in wireless links. However, the OFDM is sensitive to the four-wave mixing (FWM) among subcarriers in fiber-optics links, which is an open problem, although some initial results have been reported recently [19]. We plan to study different coding approaches to deal with FWM among subcarriers.

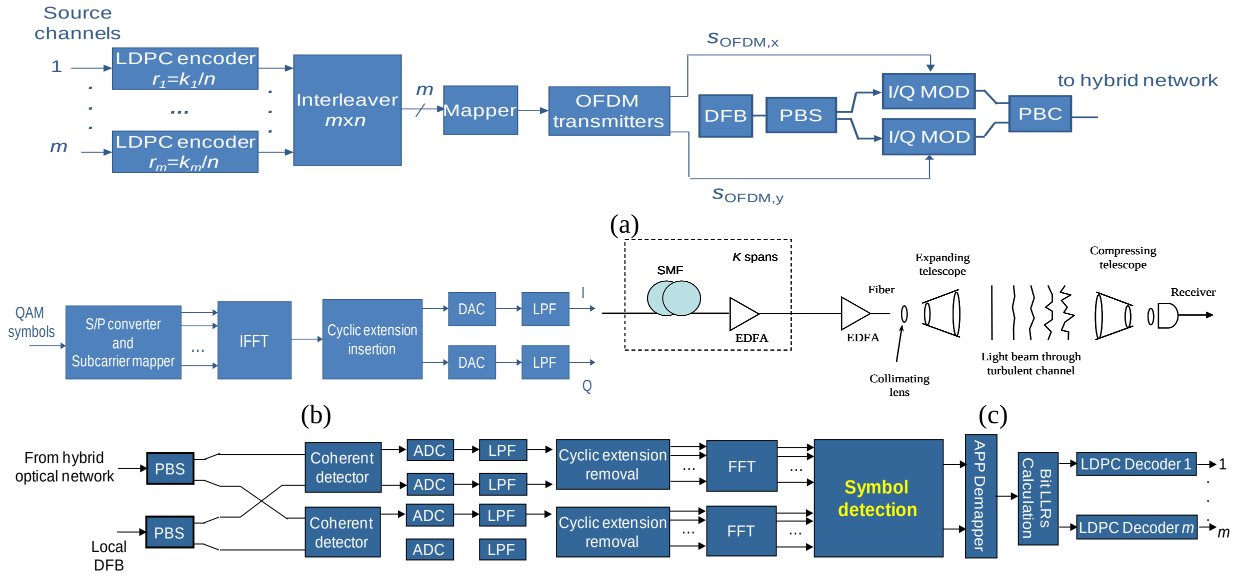

Fig. 8 The transmitter and receiver configurations for LDPC-coded OFDM hybrid optical system with polarization multiplexing and coherent detection: (a) transmitter, (b) an OFDM transmitter, (c) a hybrid optical link example, and (d) receiver architecture. PBS/PBC: polarization beam splitter/combiner, EDFA: erbium-doped fiber amplifier.

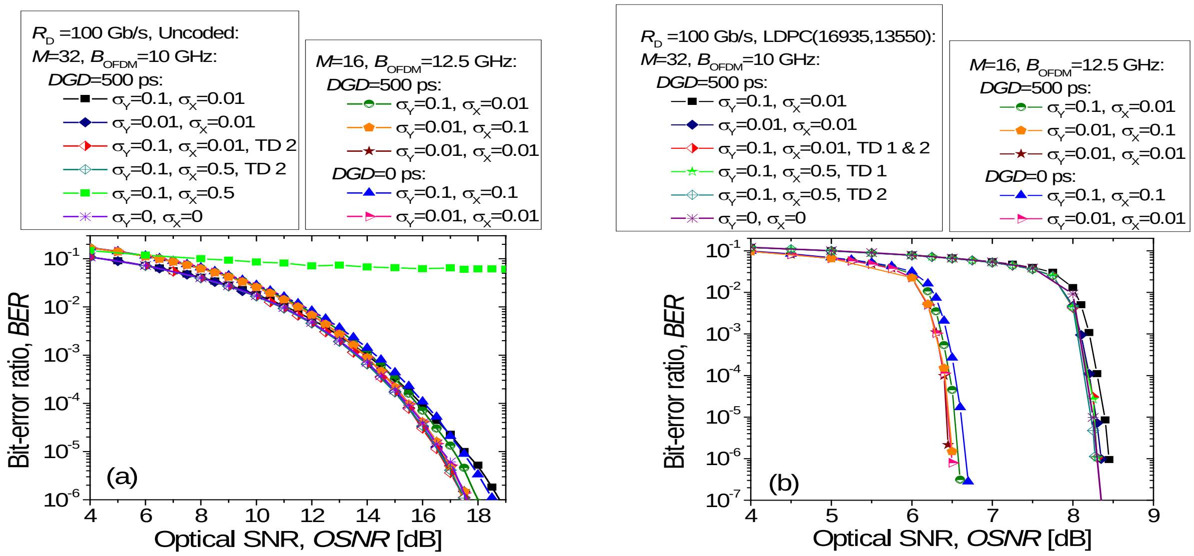

Fig. 9 BER performance of the proposed hybrid optical networking scheme: (a) uncoded BER curves, and (b) LDPC-coded BERs. B_{OFDM}: is the OFDM signal bandwidth. TD *i*: transmission diversity of order *i*. The parameter σ_x is related to the turbulence strength, while the σ_y to phase variations remained after atmospheric turbulence compensation by adaptive optics.

6.2 LDPC-Coded MIMO Hybrid Communication

The performance of hybrid communication systems can be improved by using MIMO communication techniques. In the case of FSO communications, the MIMO concept is realized by employing multiple optical sources at the transmitter side and multiple detectors at the receiver side. Although this concept is analogous to wireless MIMO concept, the underlying physics is different, and optimal and sub-optimal configurations for this channel are needed. By using the hybrid communication approach the wireless MIMO can be combined with FSO MIMO. The hybrid MIMO systems will be able to operate under severe weather conditions. We have two goals: (i) to study different techniques for coded hybrid RF-FSO MIMO communication, and (ii) to evaluate the performance of proposed techniques in terms of the achievable information rates and the channel capacity. Some preliminary results on these topics were published in our paper [11], where two types of information theoretic bounds were determined: (i) the independent identically distributed (i.i.d.) channel capacity of the MIMO optical atmospheric channels using an approach proposed by Ungerboeck [12], and (ii) the MIMO achievable information rates using Telatar's approach [13]. In the same publication ([11]), we introduced a coded-modulation scheme capable of tolerating the deep fades in the order of 20 dB and higher. The FSO channels are time-varying channels, and it is important to determine the best strategies to deal with scintillation in correlated FSO channels. In our recent paper [11] we determined the channel capacity for FSO channels with direct detection. However, the coded modulation approaches capable of reaching this channel capacity are not known, and will be determined experimentally by using the equipment to be purchased through this grant.

In our recent publications [17],[18], we described several alternative schemes suitable for PMD compensation, which do not require the increase of complexity as DGD increases. The first scheme is based on Bell Laboratories layered space-time architecture (BLAST) [14],[18], originally proposed to deal with spatial interference in wireless communications. We considered two versions of this scheme [15],[18]: zero-forcing vertical-BLAST scheme (ZF V-BLAST), and minimum-mean-square-error vertical-BLAST (MMSE V-BLAST) scheme. Because the ZF V-BLAST scheme is derived by ignoring the influence of amplified spontaneous emission (ASE) noise, we proposed the second scheme that uses the output of ZF V-BLAST scheme as starting point and removes the remaining polarization interference in an iterative fashion. The third scheme is based on Alamouti-type [16] polarization-time coding [17]. The fourth scheme is based on polarization diversity OFDM. We evaluated the performance of those schemes when used in combination with coherent detection based OFDM, and showed that those schemes are excellent candidates to deal with PMD effect in fiber-optic portion of hybrid networks. After the experimental verification of concepts we introduced in [17],[18], we plan to implement the BLAST detector and polarization interference cancellation scheme in FPGA hardware.

6.3 Adaptive Modulation and Coding (AMC) in Hybrid Communication Systems

The adaptive hybrid FSO-RF communication system, shown in Fig. 10, consists of two parallel FSO and RF channels. The LDPC encoded data stream is partially transmitted over FSO and partially over RF channel. FSO channel comprises an FSO transmitter, propagation path through the atmosphere, and an FSO receiver. The optical transmitter includes a semiconductor laser of high launch power, adaptive mapper, and power control block. To reduce the system cost, the direct modulation of laser diode is used. The modulated beam is projected toward the distant receiver by using an expanding telescope assembly. Along the propagation path through the atmosphere; the light beam experiences absorption, scattering and atmospheric turbulence, which cause attenuation, and random variations in amplitude and phase. The RF channel comprises adaptive RF mapper, RF power control, RF transmitter (Tx), transmitting antenna, wireless propagation path, receiver antenna, and RF receiver (Rx). The RF channel estimates and FSO irradiance estimates are transmitted back to transmitters using the same RF feedback channel. Because the atmospheric turbulence changes slowly, this is a plausible scenario for FSO channels with data rates in the order of Gb/s. The data rates and powers in both channels are varied in accordance with channel conditions. The symbol rates on both channels are kept fixed while the signal constellation diagrams sizes are varied based on channel conditions. When FSO (RF) channel condition is favorable larger constellation size is used, when FSO (RF) channel condition is poor smaller constellation size is used, and when the FSO (RF) channel signal-to-noise ratio (SNR) falls below threshold, the signal is not transmitted at all. Both subsystems (FSO and RF) are designed to achieve the same target bit error probability (P_b).

The overall data rate R is a function of FSO channel irradiance I and RF fading coefficient h as follows

$$R=\frac{1}{2.19}B_{\mathrm{FSO}}\log_2\left(1+K_{\mathrm{FSO}}\Gamma^{\mathrm{FSO}}(I)\frac{P^{\mathrm{FSO}}(I)}{P}\right)+B_{\mathrm{RF}}\log_2\left(1+K_{\mathrm{RF}}\Gamma^{\mathrm{RF}}(h)\frac{P^{\mathrm{RF}}(h)}{P}\right), \tag{1}$$

where $\Gamma^{\mathrm{FSO}}(I)=I^2\Gamma_0^{\mathrm{FSO}}$ and $\Gamma^{\mathrm{RF}}(h)=h^2\Gamma_0^{\mathrm{RF}}$. Γ_0^{RF} is the SNR of wireless channel in the absence of fading, while Γ_0^{FSO} is the SNR of FSO channel in the absence of scintillation. P^{FSO} denotes the power allocated to FSO channel, while P^{RF} is the power allocated to RF channel. B_{FSO} denotes the FSO channel bandwidth, and B_{RF} is the RF channel bandwidth. (K_{FSO} and K_{RF} are constants dependent on modulation format and target P_b.) To derive the optimum power adaptation policy, subject to $P^{\mathrm{FSO}}(I)+P^{\mathrm{RF}}(h)\le P$, we have to define the corresponding Lagrangian, differentiate it with respect to $P^{\mathrm{FSO}}(I)$ and $P^{\mathrm{RF}}(h)$ and set corresponding derivatives to be equal to zero. The optimum power adaptation policy is obtained as the result of this derivation:

$$\frac{K_{\mathrm{FSO}}P^{\mathrm{FSO}}(I)}{P}=\begin{cases}\frac{1}{\Gamma_{\mathrm{tsh}}}-\frac{1}{\Gamma^{\mathrm{FSO}}}, & \Gamma^{\mathrm{FSO}}\ge\Gamma_{\mathrm{tsh}}\\ 0, & \Gamma^{\mathrm{FSO}}<\Gamma_{\mathrm{tsh}}\end{cases}, \quad \Gamma^{\mathrm{FSO}}=\Gamma_0^{\mathrm{FSO}}I^2$$
$$\frac{K_{\mathrm{RF}}P^{\mathrm{RF}}(h)}{P}=\begin{cases}\frac{1}{\Gamma_{\mathrm{tsh}}}-\frac{1}{\Gamma^{\mathrm{RF}}}, & \Gamma^{\mathrm{RF}}\ge\Gamma_{\mathrm{tsh}}\\ 0, & \Gamma^{\mathrm{RF}}<\Gamma_{\mathrm{tsh}}\end{cases}, \quad \Gamma^{\mathrm{RF}}=\Gamma_0^{\mathrm{RF}}h^2 \tag{2}$$

where Γ_{tsh} is the threshold SNR, which is common to both channels. With this adaptation policy more power and higher data rates are transmitted when the FSO (RF) channel conditions are good, less power and lower data rates are transmitted when FSO (RF) channel is bad, and nothing is transmitted when the SNR falls below the threshold Γ_{tsh}.

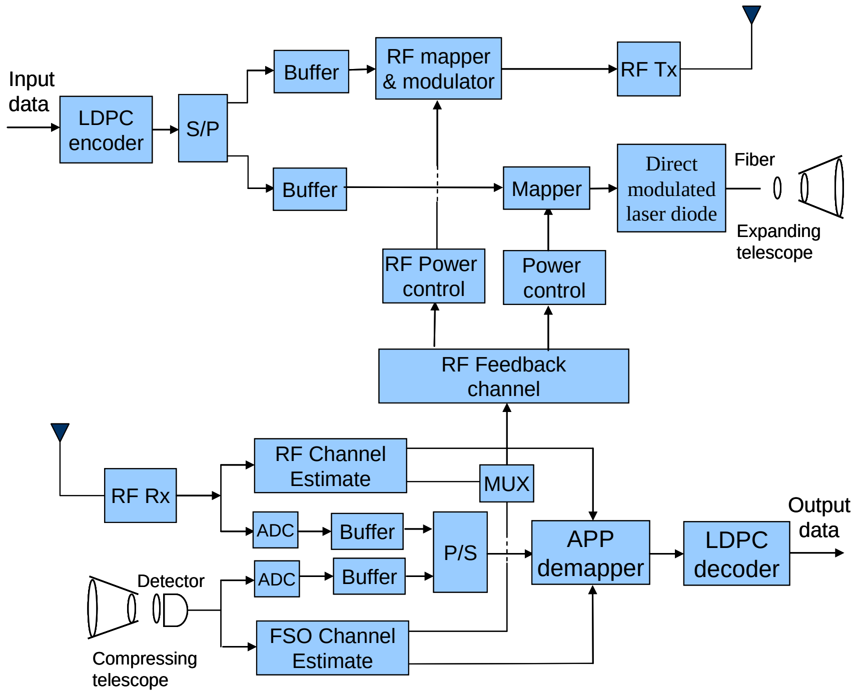

Fig. 10 The AMC scheme for communication over hybrid RF-FSO channel.

Initial results. The initial numerical results shown in Fig. 11 are obtained by employing the *block-fading* channel models, because symbol durations in both channels are much shorter than the corresponding coherence times. We therefore assume the i.i.d. fading between the blocks. The FSO channel is modeled by adopting the gamma-gamma distribution model, while wireless channel is modeled by employing the α-μ (or generalized Gamma) wireless fading model [24].

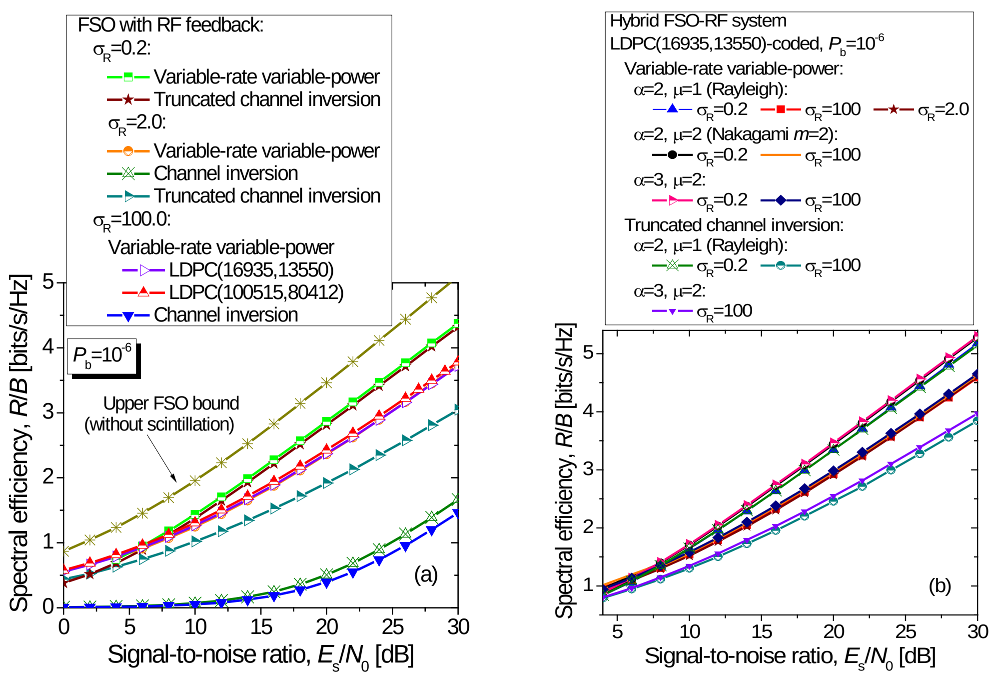

Fig. 11 Spectral efficiencies against symbol SNR for adaptive LDPC-coded modulation: (a) FSO with RF feedback only, and (b) hybrid FSO-RF system.

In Fig. 11(a), we show R/B performance of FSO system with adaptive LDPC(16935,13550)-coded MPAM for different adaptation scenarios. Given the fact that the channel capacity of FSO channel under atmospheric turbulence is an open problem, we show in the same figure an *upper bound* in the absence of scintillation. (σ_R^2 is the Rytov variance, which is used to characterize the turbulence strength. Weak fluctuations are associated with $\sigma^2_R<1$, the strong with $\sigma^2_R>1$, and the saturation regime is defined by $\sigma^2_R\rightarrow\infty$ [8].) The coding gain over adaptive modulation at $P_b=10^{-6}$ for $R/B=4$ bits/s/Hz is 7.2 dB in both (weak and strong) turbulence regimes. Larger coding gains are expected at lower BERs, and for higher spectral efficiencies. Further improvements can be obtained by increasing the girth of LDPC codes, and employing better modulation formats. The increase in codeword length to 100,515 does not improve R/B performance as shown in Fig. 11(a). It is interesting to notice that by employing adaptive coding, the communication under saturation regime is possible, as shown in Fig. 11(a). Moreover, for variable-rate variable-power scheme there is no degradation in saturation regime compared to strong turbulence regime. Overall improvement from adaptive modulation and coding for $R/B=4$ bits/s/Hz at $P_b=10^{-6}$ over non-adaptive uncoded modulation ranges from 10.5 dB (3.3 dB from adaptive modulation and 7.2 dB from coding) in the weak turbulence regime to 38.9 dB in the strong turbulence regime (31.7 dB from adaptive modulation and 7.2 dB from coding). In Fig. 11(b), we show R/B performance of hybrid FSO-RF system with adaptive LDPC(16935,13550)-coded modulation (MPAM is used in FSO subsystem and MQAM in RF subsystem) for different adaptation scenarios. For spectral efficiency of 4 bits/s/Hz at BER of 10^{-6}, the improvement of hybrid FSO-RF system over FSO system with RF feedback is 5.25 dB in Rayleigh fading ($\alpha=2$, $\mu=1$), 5.51 dB in Nakagami $m=2$ fading ($\alpha=2$, $\mu=2$) and 5.63 dB in $\alpha=3$, $\mu=2$ fading. For spectral efficiency of 2 bits/s/Hz at the same BER, the improvement of hybrid FSO-RF system over FSO system is 3.32 dB in Rayleigh fading, 3.72 dB in Nakagami $m=2$ fading and 3.86 dB in $\alpha=3$, $\mu=2$ fading. Our initial results indicate that proposed hybrid AMC scheme is an excellent candidate to deal with strong atmospheric turbulence in FSO links. We also plan to study the use of adaptive coding in fiber-optics portion of hybrid network. For example, the optical SNR (OSNR) monitoring channel can be used for adaptation. The monitoring channel can be used in opposite direction (from receiver side to transmitter side), and then based on channel conditions we can adapt the constellation size and code rate. We plan to extend this study to the case when the channel state information is uncertain, perform proof-of-concept experimental validation, implement corresponding encoders and decoders in FPGA hardware, and demonstrate the first real-time hybrid FSO-RF communication system.

6. 3. 1 Rate Adaptive Coding for Communication over Hybrid Communication Links

A rate adaptive code (also known as rate-less code) is an error-correcting code whose rate can be changed according to the time-varying channel conditions. Two classes of codes will be investigated here (i) *punctured codes* (the rate is varied by puncturing the parity bits so that the effective code rate is increased) and, (ii) *fountain codes* [20], in particular *Raptor codes* [21] (the rate is changed by increasing the codeword length). A *Raptor code* is obtained by concatenating an inner error-correcting code (the pre-code), with an outer Luby-transform (LT) code. An LT Code [20],[22] is a sparse random linear code, with a very simple encoding and decoding algorithms. LT encoding process can be described as follows. Each encoded symbol $\boldsymbol{x}_n$ is generated from the message symbols $\boldsymbol{s}_1,\ldots,\ \boldsymbol{s}_{K,\mathrm{LT}}$ through two steps: (i) randomly choose the degree d_n from a degree distribution set Ω, and (ii) choose uniformly at random d_n distinct input symbols, and set $\boldsymbol{x}_n$ equal to the bitwise sum, modulo 2, of those d_n symbols. The decoder's task is to recover $\boldsymbol{s}$ from $\boldsymbol{x}=\boldsymbol{sG}$, where $\boldsymbol{G}$ is the matrix associated with the graph (the pseudorandom matrix) by sum-product algorithm, as in [22].

Although the encoding and decoding algorithms are simple, LT codes have the following two drawbacks: (i) d_n can take any integer value up to the size of the input word, leading to a decoding complexity $O(K_\mathrm{LT} \log K_\mathrm{LT})$, where K_LT denotes the information symbol-word length, and (ii) the error floor is observed at high SNRs. To solve both problems simultaneously, we propose to use the raptor code concept. In our proposal, a Raptor code is formed by concatenating an inner systematic LDPC code with an outer LT code, as shown in Fig. 12(a). Since inner LDPC code is systematic we can modify the original bipartite graph as illustrated in Fig. 12(b), and perform joint LT-LDPC soft decoding on such obtained bipartite graph. We will study low-complexity soft-decoding schemes for joint LT-LDPC decoding based on modified bipartite graph shown in Fig. 12(b), and implement corresponding decoders in FPGA. Notice that design of outer LDPC codes optimal for communication over hybrid links is an open problem, which will be addressed in this research.

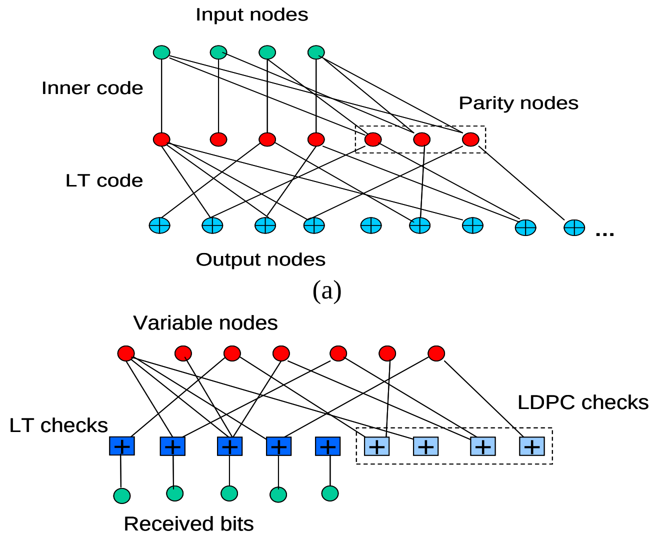

Fig. 12 (a) The bipartite graph of a raptor code, (b) modified bipartite graph for joint LDPC-LT decoding.

6.4 LDPC-Coded Turbo-Equalization (TE) in Hybrid Communication Systems

In this section we describe an LDPC-coded turbo equalization scheme [6], as a universal scheme that can be used simultaneously for: (i) suppression of fiber nonlinearities, (ii) PMD compensation, (iii) chromatic dispersion compensation and (iv) wireless multipath distortions compensation in multilevel coded-modulation schemes. The LDPC-coded turbo equalizer is composed of two ingredients: (i) the multilevel Bahl-Cocke-Jelinek-Raviv (BCJR) algorithm [23] based equalizer, and (ii) the LDPC decoder. The transmitter configuration, for multi-level coding (MLC), is already explained Section 6.1 (see Fig. 8(a)). The receiver configuration of LDPC-coded turbo equalizer is shown in Fig. 13(a). The outputs of upper- and lower-balanced branches, proportional to Re$\{S_iL^*\}$ and Im$\{S_iL^*\}$ respectively, are used as inputs of multilevel BCJR equalizer, where the local laser electrical field is denoted by L and incoming optical signal at time instance i with S_i. The multilevel BCJR equalizer operates on a discrete dynamical trellis description of the hybrid channel with memory. This dynamical trellis is uniquely defined by the following triplet: the previous state, the next state, and the channel output. The state in the trellis is defined as $\boldsymbol{s}_j=(x_{j-m},x_{j-m+1},..,x_j,x_{j+1},\ldots,x_{j+m})=\boldsymbol{x}[j-m,j+m]$, where x_k denotes the index of the symbol from the following set of possible indices $\boldsymbol{X}=\{0,1,\ldots,M-1\}$, with M being the number of points in corresponding M-ary signal constellation such as M-ary PSK, M-ary QAM or M-ary polarization-shift keying (PolSK). Every symbol carries $l=\log_2 M$ bits, using the appropriate mapping rule (natural, Gray, anti-Gray, etc.) The memory of the state is equal to $2m+1$, with $2m$ being the number of *symbols* that influence the observed symbol from both sides. An example trellis of memory $2m+1=3$ for 4-ary modulation formats (such as QPSK) is shown in Fig. 9(b). The trellis has $M^{2m+1}=64$ states ($\boldsymbol{s}_0$, $\boldsymbol{s}_1,\ldots$, $\boldsymbol{s}_{63}$), each of which corresponds to the different 3-symbol patterns (symbol-configurations). The state index is determined by considering ($2m+1$) symbols as digits in numerical system with the base M. For example, in Fig. 13(b), the quaternary numerical system (with the base 4) is used.

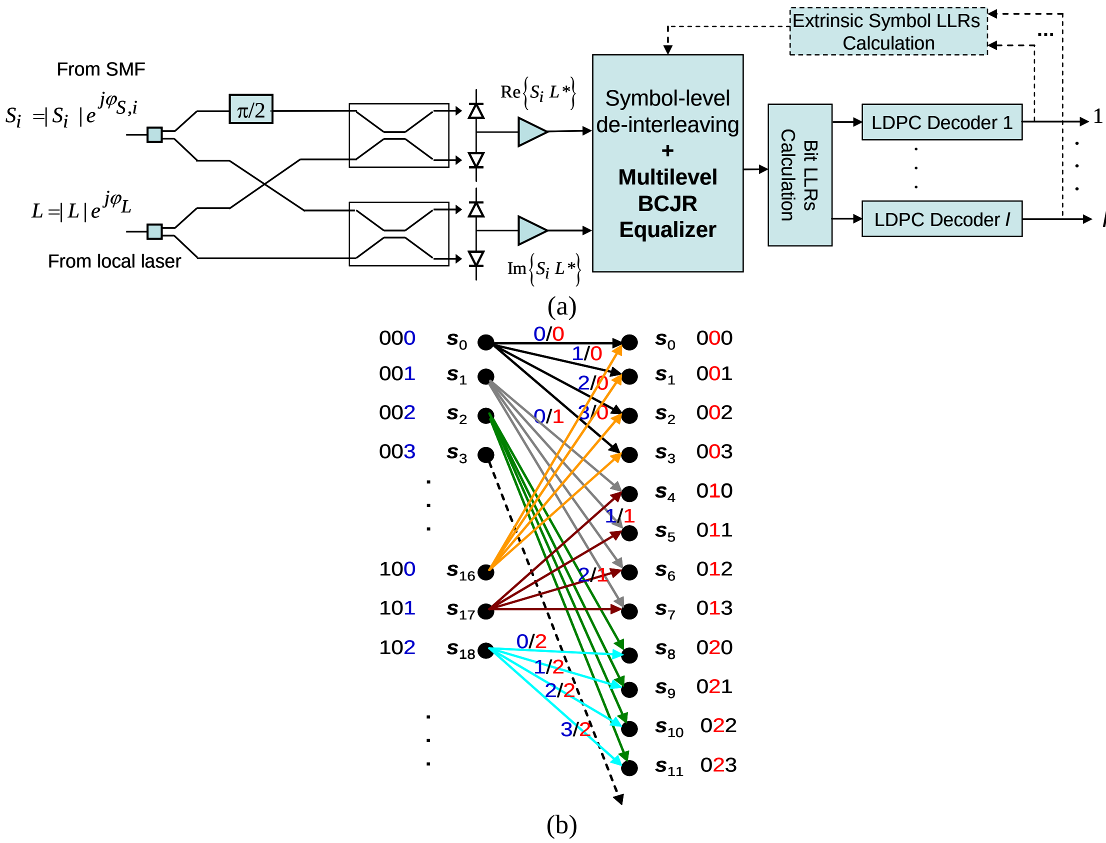

Fig. 13 (a) LDPC-coded turbo equalization scheme configuration, and (b) a portion of trellis for 4-level BCJR equalizer with memory $2m+1=3$.

From Fig. 13(b) it is evident that the complexity of dynamic trellis grows exponentially, because the number of states is determined by M^{2m+1}, so that the increase in signal constellation leads to increase of the base, while the increase in channel memory assumption ($2m+1$) leads to the increase of exponent. For large constellations and longer memories, the reduced complexity multilevel BCJR algorithm to be developed, should be used instead. For example, instead of detection of sequence of symbols corresponding to the length of codeword n, we can observe shorter sequences. Further, we do not need to memorize all branch metrics but several largest ones. In forward/backward metrics' update, we need to update only the metrics of those states connected to the edges with dominant branch metrics, and so on. In order to study the efficiency of this method to compensate for various hybrid channel impairments simultaneously, the purchase of real-time scope and spectrum analyzer is needed.

6.5 Hybrid FSO/RF Satellite Networks

Recently, there has been significant interest in spectrum-agile software-defined radios (a.k.a. cognitive radios or CRs) to be used in a variety of military and commercial applications. On the commercial side, such systems provide a much needed solution for improving the spectral efficiency of under-utilized portions of the licensed spectrum (particularly, the TV "white spaces" in the 470-698 MHz range). On the military side, these systems can facilitate inter-operability between different radio platforms and also enable prolonged RF communications in the presence of dynamic fluctuations in channel quality. However, these systems suffer from jamming and interference, in addition to low speeds. To solve these problems simultaneously we plan to use the use of hybrid FSO/RF communication scenario. Namely, the FSO links do not suffer from interference and jamming. Although FSO technology can remedy the interference, jamming and capacity problems of classic satellite technologies, its reliability is affected by atmospheric turbulence in clear weather and by low visibility in foggy conditions. RF signals are not impacted by these problems, suggesting a joint (complementary) operation of a hybrid FSO/RF channel. Novel adaptive energy-efficient channel coding techniques and networking protocols will be studied to enable such networks to deal simultaneously with different channel impairments, including atmospheric turbulence for the FSO subsystem and multipath fading for the RF subsystem.

Other topics that will benefit from this purchase include research on deep-space optical communications [25]-[27], orbital angular momentum (OAM) based modulation [28],[29], adaptive LPDC-coded modulation [30], optimum signal constellation design [31], multidimensional signaling [32],[33], just to mention few.

6.6 Multidimensional QKD

QKD is one of the most promising concepts in quantum information theory [34]–[37]. The impossibility for an eavesdropper to tap the quantum channel and distinguish between non-orthogonal states without introducing disturbance to the channel ensures that the QKD system is quite secure. Accordingly, a wide range of applications in both government and industry can be envisioned, in which security does not depend on prohibitive increases in processing power and complexity of algorithms applied to protect the integrity of information flows. Even though significant advances have recently been made in QKD research and commercialization for both free-space and fiber optic channels, the transmission speeds of the secure quantum key exchange are still low. Most research efforts so far have been focused on two-dimensional qubits implemented on two nonorthogonal photon polarization states. However, since photons can also carry both spin angular momentum (SAM) associated with polarization, and orbital angular momentum (OAM), associated with the azimuthal phase of the complex electric field, additional degrees of freedom can be utilized for quantum communication purposes.

Several methods have recently been proposed to increase the information content of photons for quantum communications [38]-[43]. These methods rely on encoding information either using time and frequency, linear momentum, or using multiple degrees of freedom made available through hyper-entangled states. However, in all of these schemes the problem of phase front distortion and its impact to the quantum channel capacity was not fully adressed. Moreover, no detail consideration has been given to the integration of information reconciliation and privacy amplification.

In our approach we will investihate and define the model based on use of the TAM for QKD ovwer free space optical channels. As mentioned earlier, photons can carry both SAM, associated with polarization given by $\sigma\hbar= \pm 1$ (for circular polarization), and OAM, associated with azimuthal phase of the complex electric field. Each photon with azimuthal phase presented by $\exp(-jl\phi)$ (l=0,±1,±2,…) can carry an OAM of $l\hbar$. We can associate a TAM, given by the sum of SAM and OAM with each photon, with eigenvalue equal $j\hbar = (\sigma+l)\hbar$. Since OAM eigenstates are orthogonal, it permits that an arbitrary number of bits per single photon can be transmitted. The ability to generate/analyze states with different TAM, by using interferometric or holographic methods, allows the realization of quantum states in multidimensional Hilbert space. The key for QKD over TAM based states is to enable proper generation. Multiplexing and demultiplexing of OAM states, as well as to overcome issues related to data rate limitations and QKD information reconciliation and privacy amplification.

We plan to perform information reconciliation by multilevel coding (MLC) using component LDPC codes with a large-girth. This approach is applicable to arbitrary number of bits per photon. The component LDPC codes will be designed by taking the physics of FSO channel into account. The photodetection of parity symbols will be performed by photon-counting receivers that will be bought through this project, which are essential for overall experimental realization. The number of redundant bits for LDPC coding will be determined from conditional entropy $H(\mathrm{Q}(Y)|X)$. Accordingly, we plan to develop novel advanced protocols that will exploit non-orthogonal TAM states for multidimensional QKD and employ information reconciliation and privacy amplification. With this approach, we will increase the total number of degrees of freedom associated with a single photon through initiation of multiple Laguerre-Gaussian states over the same optical beam.

As an illustration, in Fig. 14 we show our initial results on FSO channel capacity under effects of both atmospheric turbulence and an imperfect generation/strong coupling of OAM modes. In this project, we plan to extend the model to TAM quantum channel structure and capacity calculations.

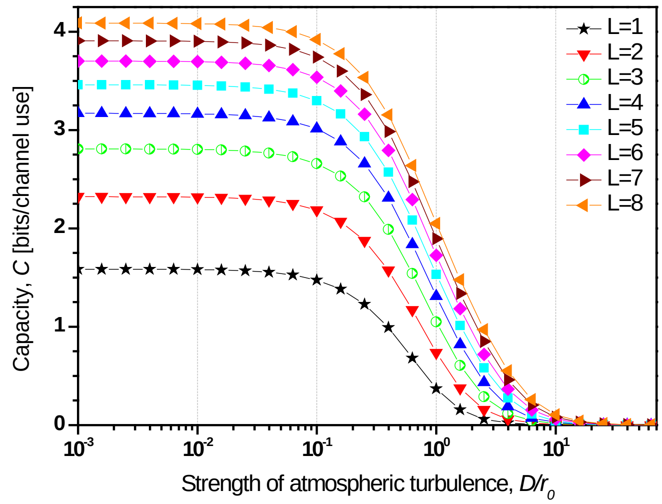

Fig. 14 Quantum channel capacity for the OAM based FSO QKD shown versus atmospheric turbulence strength (in terms of telescope diameter, *D*, over Fried's coherence diameter, r_0).

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APPENDIX

UNIVERSITY OF ARIZONA
SPONSORED PROJECTS SERVICES
FINAL PROPERTY REPORT AS OF AUGUST 14, 2016

United States Army Research Office							
W911NF-15-1-0387							
3015210							
Description	**Title Code**	**Title Description**	**Manufacturer Name**	**Model Number**	**Asset Total**	**Account Total**	**In Service Date**
Arbitrary waveform generator with memo	55062	US Army - UA Owne	TEKTRONIX	AWG70002A	$ 72,393.75	$ 72,393.75	9/10/2015
Analyzer, 33 GHz digital serial, 50 GSa/s rea	55062	US Army - UA Owne	TEKTRONIX	DSA73304D	$ 77,520.00	$ 77,520.00	9/10/2015
Module, Pluto-Telco 013-C Phase Only spa	55062	US Army - UA Owne	HOLOEYE CORPO	HES 6010-TELCO-013-C	$ 12,595.00	$ 12,595.00	10/12/2015
Module, Pluto-Telco 013-C Phase Only spa	55062	US Army - UA Owne	HOLOEYE CORPO	HES 6010-TELCO-013-C	$ 12,595.00	$ 12,595.00	10/12/2015
Module, Pluto-Telco 013-C Phase Only spa	55062	US Army - UA Owne	HOLOEYE CORPO	HES 6010-TELCO-013-C	$ 12,595.00	$ 12,595.00	10/12/2015
Module, Pluto-Telco 013-C Phase Only spa	55062	US Army - UA Owne	HOLOEYE CORPO	HES 6010-TELCO-013-C	$ 12,595.00	$ 12,595.00	10/12/2015
Single Photon Counting Module 950-1600 r	55062	US Army - UA Owne	Laser Componen	COUNT-Q	$ 12,511.51	$ 12,511.51	12/18/2015
Single Photon Counting Module 950-1600 r	55062	US Army - UA Owne	Laser Componen	COUNT-Q	$ 12,511.52	$ 12,511.52	12/18/2015
Single Photon Counting Module 950-1600 r	55062	US Army - UA Owne	Laser Componen	COUNT-Q	$ 12,511.52	$ 12,511.52	12/18/2015
Single Photon Counting Module 950-1600 r	55062	US Army - UA Owne	Laser Componen	COUNT-Q	$ 12,511.52	$ 12,511.52	12/18/2015
Multi-DM MEMS Deformable mirror, conti	55062	US Army - UA Owne	BOSTON MICRO	N/A	$ 26,945.00	$ 17,928.18	1/20/2016
					$277,284.82	$268,268.00	